U.S. Department of Energy
Advanced Manufacturing Office

CABLE Big Idea RDD&D Workshop

DRAFT Read-ahead Document

April 7-9, 2021

Preface

The purpose of this document is to provide background information for those individuals who will be participating in the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE), Advanced Manufacturing Office (AMO) CABLE Workshop April 7-9, 2021. Please review this document prior to the workshop to enable better engagement in the workshop discussions.

This document provides information on:

- AMO Overview and Workshop Purpose
- CABLE Applications
- CABLE Materials
- CABLE Characterization

1. AMO OVERVIEW AND PURPOSE OF WORKSHOP

1.1 Advanced Manufacturing Office (AMO) & CABLE Team Overview

AMO supports R&D projects, R&D consortia, and early-stage technical partnerships with national laboratories, companies (for-profit and not-for-profit), state and local governments, and universities through competitive, merit-reviewed funding opportunities designed to investigate new manufacturing technologies.

AMO's R&D projects explore novel energy-efficient, next-generation materials and innovative process technologies for both targeting specific industry sectors and a wider range of manufacturing industries. In addition, R&D projects focus on foundational or advanced energy technologies across multiple industry sectors. All of AMO's R&D investments are high impact, use project diversity to spread risk, target nationally important innovations at critical decision points, and contribute to quantifiable energy savings.

The Conductivity-enhanced materials for Affordable, Breakthrough, Leapfrog Electric and thermal applications (CABLE) winning Big Idea was supported by 9 offices withing the U.S. Department of Energy. It is lead by AMO within EERE and also includes the Office of Electricity and 7 other Offices within EERE including the Building Technologies Office (BTO), the Geothermal Technologies Office (GTO), the Hydrogen and Fuel Cells Technology Office (HFTO), the Solar Energy Technologies office (SETO); the Vehicle Technologies Office (VTO) the Water Power Technologies Office (WPTO) and the Wind Energy Technologies Office (WETO). CABLE's research, development, demonstration and deployment (RDD&D) efforts support the Biden Administration goals to address the climate crisis by decarbonization through electrification and increasing infrastructure resilience while creating new high paying jobs for Americans.

1. https://www.energy.gov/eere/amo/advanced-manufacturing-office

1.2 Workshop Purpose

Conductive materials are fundamental to nearly all energy use applications. Developing manufacturing processes for enhanced-conductivity materials would enable product manufacturers to lower costs, improve performance, and allow their customers and the US to substantially improve energy efficiency and reduce GHG and CO_2 emissions.

AMO is hosting this workshop to gather information on the state-of-the-art in **C**onductivity-enhanced materials for **A**ffordable, **B**reakthrough **L**eapfrog **E**lectric and thermal applications (CABLE) from stakeholders, including scientists, engineers, manufacturers, materials experts, and utilities, on potential areas for future R&D and program activities.

This workshop is a result of collaboration by several DOE offices, including the Office of Electricity, ARPA-E, the Office of Science, Basic Energy Sciences (BES), Vehicle Technologies, Solar Energy, Water Power, Wind Energy, and Building Technology Offices, all led by AMO. DOE is inviting expert advice from several DOE national laboratories, universities, and companies to better understand the current research status in this area and optimal future research directions.

The workshop will consist of three afternoon sessions. On Day 1, participants will learn about the CABLE concept and will participate in facilitated discussions on applications for highly conductive materials. On Day 2, experts will share the state-of-the-art of metallic and non-metallic conductive materials science/theory. On Day 3, participants will learn and discuss modern conductor characterization methods, material supply chains, and current international and U.S. patenting environments.

Attendees are encouraged to actively contribute to the facilitated discussions to share their broad views, experiences, and insights. At the end, discussion groups will report on their deliberations and conclusions. Workshop proceedings will be recorded to ensure that all discussions are captured accurately in the conference report, though information or views included in workshop outputs will be not be attributed to an individual or specific organization/company. To enable open conversations, neither the recording, nor panel presentations will be available to the general public. Introductory and plenary presentations, however, will be available at *https://cable-bigidea.anl.gov/workshop/*.

1.3 Background

As electrification grows worldwide in response to the climate crisis, so too will demand for conductivity-enhanced materials and applications. The International Energy Agency estimates that 10 million miles of new transmission cable will be needed to connect renewables to the planet's grids in the next decade [1]. That's enough cable to reach the moon and back 21 times.

There is an urgent need for enhanced conductivity materials that can lower costs and improve performance of transmission cables—including resilience against extreme weather events. To increase efficiency and reliability, aging electric and transportation infrastructures should be replaced with new high-performance materials. Furthermore, enhanced conductivity materials support new transformational technologies ranging from electric cars, trains, planes to smartphones, heat pumps and everything else in our daily lives that involves the conduction of electric and thermal energy.

1. IEA (2020), *Electricity security in tomorrow's power systems*, IEA, Paris. https://www.iea.org/articles/electricity-security-in-tomorrow-s-power-systems

1 CABLE Materials in Manufacturing

2.1 Applications

Electrical conductors are ubiquitous and can be found in nearly every technology. Improving the electrical conductivity, along with other mechanical properties, of the materials would have profound effect on certain industries and applications.

2.1.1 Electricity Delivery Systems

The U.S. Electricity Delivery System (EDS) is currently undergoing a transformation as it balances improvements in grid reliability and resilience while protecting itself from evolving threats, such as cyber-attacks and extreme weather [1]. In addition, a diversity of new resources is being connected to the grid as federal, state, and local policies mandate increased penetration of renewable energy and distributed energy resources. To ensure efficient, reliable, and secure electricity delivery in the U.S. electrical grid, technological advancements in Transmission & Distribution (T&D) infrastructure are required. Specifically, impactful would be more highly efficient transmission cables [2].

Conductor Manufacturing Prize

This Workshop is connected to DOE's CABLE Conductor Manufacturing Prize, hosted by the American Made Challenges. The program was developed to help energize American ingenuity and empower innovators, connecting them with DOE national labs, incubators, accelerators, and other facilities in the American Made network to turn disruptive ideas into reality, in a matter of months instead of years.
The CABLE prize has **3 Stages**:

Stage 1 focuses on concepts to develop conductors with electric conductivity enhancements of 7.5% over today's best copper and aluminum conductors. **Stages 2** and **3** address testing lab-scale high-performance properties and then evaluating manufacturing scale-up, including the manufacturing and cost.

Manufacturing Prize
Electrical
Conductivity Enhancement Goals*

*Must be met at the microscale, i.e., 1-gram minimum sample size

International Annealed Copper Standard (IACS) set in 1913 as 100% IACS = 58.1 X106 Siemens /meter at 20°C.
Ag-enhanced: >113% IACS
Cu-enhanced: >109% IACS
Al-enhanced: >67% IACS
Nonmetal-enhanced: >50% IACS

The electricity infrastructure that transports and distributes power from generation sources to customers is often overlooked in the effort to lower energy cost and emissions, though improvements to the electricity delivery system are essential to meeting the needs of a decarbonized, resilient, and secure future grid. Significant investment in advanced transmission cables could help reduce greenhouse gas emissions.

Overhead power lines are predominantly aluminum-based and underground or undersea lines are often copper-based, but current research areas in other configurations and chemistries aim to minimize resistance and cost, and maximize conductivity, strength, and reliability. As a material, aluminum has potential for overhead lines, and advanced manufacturing methods may yield unique advancements for aluminum-based conductor [3]. Basic materials research is required to develop more advanced conductors, but other important areas of focus also include designs that conform to specific requirements (i.e., ASTM or Rural Utilities Service standards) and conductor-adjacent components such as advanced insulators, coatings, and sensors.

DOE seeks to integrate affordable, high-performance conductors into T&D infrastructure providing numerous benefits for EDS and other power-carrying applications (including overhead, underground, and underwater cables). Lines or cables with significantly improved characteristics yield transmission benefits including minimized losses, increased strength, reduced sag, and improved carrying capacity, all of which improve performance and operations. For the US, an improved EDS would lead to more energy independence and resilient. For grid operators, advanced T&D lines and cables would increase grid reliability. For customers, use of such lines and cables would result in energy and cost savings.

1. De Martini, P. "Future of U.S. Electric Distribution." EEI, PNNL, October 2010. https://gridarchitecture.pnnl.gov/media/white-papers/2012%20Jul-Future%20of%20Electric%20Distribution.pdf

2. U.S. DOE, Office of Electricity. "Transformer Resilience and Advanced Components (TRAC) Program." U.S. DOE, June 2020. https://www.energy.gov/sites/prod/files/2020/06/f75/TRAC%20Program%20Vision%20and%20Framework.pdf

3. Balser, A., et al. "Effective Grid Utilization: A Technical Assessment and Application Guide." NREL, September 2012, https://www.nrel.gov/docs/fy13osti/53696.pdf

2.1.2 Transportation

Electrical conductors have been integral in many public transportation systems including trains, subways, and busses for many decades. More recently though, personal electric vehicles are becoming an increasing critical component of transportation needs with the popularity and accessibility of electric vehicles. Likewise, electrical power is being considered for air transportation due to increased power density of batteries and the need to de-carbonize the industry.

2.1.2.1 Ground Transportation

As more and more vehicles are electrified, the energy losses in the charging couplers used to recharge these vehicles will continue to grow, especially as ever faster charging times are considered [1]. Improvements in the conductive materials used in the wire and contacts in the SAE J1772 DC charging coupler and cable, that operate at up to 400A and 1000V, are sought to reduce these energy losses. DOE will discuss CABLE materials for new designs for wires and charging couplers for use in the recharging of electric vehicles.

On the demand side, electric motors consumed more 50% of all electrical energy in the US and more than 85% of industrial electrical energy [#]. Motor-driven components used in HVAC and refrigeration are the highest energy consumers in the buildings sectors. Most of the residential and commercial equipment types covered in those sectors are covered by DOE energy conservation standards and industry standards such as ASHRAE 90.1. These standards continue to push manufacturers to consider both more efficient motors and variable-speed technologies, among other product design improvements, to meet more stringent minimum efficiency requirements. However, research efforts and incentives outside of DOE regulation would enable further reductions in motor-driven system energy consumption in the residential and commercial sectors.

Proposed improvements to material and coupler designs must consider all requirements for EV couplers including thermal, electrical, and other safety standards while not decreasing cable flexibility or increasing the weight from existing cable designs. The lifetime energy loss reductions from the proposed material and coupler design should be calculated for the entire cable system from the Electrical Vehicle Supply Equipment to the inlet of the vehicle. The impact of corrosion, fatigue, thermal degradation, and other impacts to the material lifetime should also be considered.

1. U.S. Department of Energy. “Batteries, Charging, and Electric Vehicles.” US DOE, Office of Energy Efficiency and Renewable Energy, 2020, *https://www.energy.gov/eere/vehicles/batteries-charging-and-electric-vehicles*.

2.1.2.2 Air Transportation

Electric aviation has the potential to eliminate significant direct carbon emissions, drastically reduce fuel consumption, minimize noise pollution, and decrease maintenance costs [1]. DOE seeks novel technology aimed at enhancing the performance of components applied to large electric-propelled passenger (e.g., twin-aisle) airplanes. Opportunities to implement electric aviation include improving electric motor performance and electrical power delivery from enhanced electrically conductive wiring materials, electrical insulation materials designed to minimize arc formation, and high thermal conductivity materials to enhance heat transfer.

The state-of-the-art maximum onboard electric power generation capacity in operating commercial airliners is approximately 1 MW on the Boeing 787 which is supplied via low-voltage AC distribution (115-235 VAC, ±270 VDC) to ancillary electrical power systems such as HVAC, avionics, actuators, and anti-icing. Airbus' testbed design for a narrow-body, hybrid-electric distribution system, the E-Fan X, includes a distribution system at 3 kV and a 2 MW electric propulsor which replaces one of four jet engines. However, an all-electric propulsion system for a twin-aisle (e.g., NASA N3-X) aircraft would require at least 50 MW (i.e., utility-scale power) during takeoff, which is significantly higher than the present onboard generation and power distribution system capabilities. Rolls-Royce and GE research projects funded by NASA have concluded that even with a high temperature superconductor, voltages are optimally in the range of ±4.5-12 kV to achieve the power density required of power electronics and motors for 50 MW of total system power. The distribution of such a large amount of power may require the use of a prohibitive load of cables, connectors, and circuit breakers.

Transformative solutions such as the use of a medium-voltage distribution system and novel conducting materials that would be more likely to meet the weight and size requirements. In addition to the power density concerns, the distribution system will also have to meet the safety and reliability demands for aerospace applications in extreme environmental conditions (pressure, temperature, vibration, shock, etc.). In particular and most importantly, at medium voltage and low atmospheric pressures the risk of partial discharge becomes a concern. There are several unique challenges that will need to be addressed with various possible solution spaces to achieve greater than 50MW aerospace power distribution.

The broad objectives are to identify appropriate wiring materials with optimum gravimetric power densities and minimum electrical losses, and evaluate corresponding vacuum or cryogenic systems if necessary. The targeted outcome is to increase the power distribution capability on electric aircraft with minimal impact on weight while maintaining the high reliability and safety requirements of aviation.

1. Brelje, B.J., Martins, J.R.R.A., "Electric, hybrid, and turboelectric fixed-wing aircraft: A review of concepts, models, and design approaches," Progress in Aerospace Sciences, 104, pp. 1-19, 2019. https://doi.org/10.1016/j.paerosci.2018.06.004

2.1.3 Energy Efficiency

Increasing the efficiency of any energy consuming process is a step in the right direction for the U.S. Two of the larger consumers of energy, and thus offer the most impact of energy and resource minimization, are the Building sector and the Industrial sector.

2.1.2.1 Building Efficiency

U.S. buildings accounted for nearly 40% of the nation's man-made carbon dioxide emissions, 18% of the nitrogen oxide emissions, and 55% of the sulfur dioxide emissions [1]. These emissions—primarily from electricity generation—in turn contribute to smog, acid rain, haze, and global climate change. Improving the efficiency of the nation's buildings can play a significant role in reducing pollution.

Thermal energy storage has great potential to reduce energy use and CO_2 emissions from buildings. Two-phase systems, such as water-ice, are attractive for thermal energy storage because of the relatively large heat of fusion resulting in high energy density, low cost, near constant storage temperature along with minimal environmental impact. Applications of ice storage include heating, ventilation, and air-conditioning and refrigeration technologies [2].

During ice storage charging, a heat transfer fluid at a lower temperature is used to form ice, and during discharging, the process is reversed and ice melts into water and the heat transfer fluid is cooled down. The challenge with ice storage is that ice is a relatively poor thermal conductor. Thus, as ice is formed it becomes kinetically prohibitive to form more ice, limiting the total amount of stored energy over a fixed period. Typically, extensive piping is used to increase the total energy stored. Moreover, this approach leads to increased overall footprint and cost of the storage systems often making them marginally- or non-economical.

DOE seeks research directions to overcome the issues associated with thermal energy storage through new materials and thermal control approaches. DOE is interested in both passive and active approaches such as novel materials, high conductivity reinforcements, tunable conductivity, and use of external stimuli to control thermal conductivity.

Integrating energy-efficiency solutions into the highly productive U.S. construction practices for new buildings and retrofits is one way in which the U.S. can reduce its carbon footprint and improve efficiency. Another solution is to consider high performance new designs for existing technologies such as heat pumps and air conditioners that improve the energy efficiency of U.S. buildings. Leveraging CABLE non-metallic materials with enhanced thermal conductivity in U.S. buildings and building technologies is an affordable and highly accessible way to support performance improvements that make energy savings a reality.

1. International Energy Agency and the United Nations Environment Programme (2018): 2018 Global Status Report: towards a zero-emission efficient and resilient buildings and construction sector.
2. "Thermal Energy Storage for Space Cooling, Technology for reducing on-peak Electricity Demand and Cost." DOE/EE-0241, 2000, https://www.osti.gov/servlets/purl/770996, doi:10.2172/770996

2.1.2.2 Industrial Efficiency and Decarbonization

The industrial sector consumes about 54% of the world's delivered energy [1]. Because of its large energy use, increasing the efficiency of industrial process even small amount can have enormous impacts on energy savings and consequently reduced GHG emissions. Specific improvements can be realized in motors, combined heat and power systems, heat exchangers, and waste heat recovery by using increased electrical and thermal conductor materials.

AMO supports the development and scale up of industrial processes powered only by electricity produced from zero carbon energy sources. The climate crisis is one of the major challenges we face as a planet. The industrial sector contributes 22% of greenhouse gas emissions in the U.S. and is challenging to decarbonize due to the complexity and inhomogeneity of the emissions sources [2]. There are multiple pathways to achieve industrial decarbonization and, due to the urgency of the climate crisis, these pathways must be pursued in parallel. Electrification of industrial processes, coupled with the use of zero-carbon power sources, is an important strategy to decarbonization that could yield other benefits such as greater energy efficiency and improved quality control [3[. AMO's goal is to achieve significant industrial decarbonization by 2030.

1. "International Energy Outlook 2016", U.S. Energy Information Administration, https://www.eia.gov/outlooks/ieo/pdf/0484(2016).pdf
2. Sources of Greenhouse Gas Emissions. U.S. Environmental Protection Agency. 2021. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions
3. Plugging in: What electrification can do for industry. McKinsey & Company. May 2020. https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/plugging-in-what-electrification-can-do-for-industry

2.1.4 Renewables

It is understood that in the face of global climate change, renewable energy sources such as solar, geothermal, wind, and water power, will play a vital role in de-carbonizing energy production and reducing the disruption of global climate patterns. As renewables are often smaller-scale and in more remote locations than the fossil power they would replace, proportionately more electrical conductors transmitting power from generation source to consumers will be needed. In addition, the conductors must be resilient against climate impacts including extreme temperatures and storms. The renewable generation itself can benefit in numerous ways from enhanced conductivity materials

2.1.4.1 Solar Energy

Concentrating Solar Power uses thermally and electrically conducting materials similar to those used in geothermal and to a lesser extent, wind and water for heat exchangers and generators.

In **Photovoltaic (PV) cells**, metal conductors extract the charges that light generates in PV cells so they can flow to a PV array. These electrical conductors include the metal contacts, wiring, and connectors. Innovative technologies and approaches are required that improve the quality and performance of PV electrical connections at the cell, module, and system level while reducing their cost. Of specific interest are the application of new conductive materials and related technologies to advance the state-of-the-art in two areas:

- **Cell and module metal contacts and interconnects**
  There are strict requirements for making high-performance contacts and interconnects. Improvements in contact conducting materials are needed to increase the conductivity and durability while reducing their total cost of processing and raising the overall module performance. Applying the contact to the solar cell must:
  (1) introduce minimal recombination centers at the interface of the metal and the absorber material, because it would reduce the power output.
  (2) form an energetically favorable path at the interface for charges to move from the absorber material to the metal.
  (3) be conductive enough to carry charges out of the cell without appreciable loss due to series resistance or shadowing.
  These technical requirements must all be met while maintaining low cost, reliability, durability over decades, and compatibility with the packaging materials and existing manufacturing processes.

- **PV system electrical connections**
  Innovations in wire management and cable attachment present an opportunity to extend system durability well beyond the traditional 25-to-30-year PV system life. SETO's goal is to extend the operational life of PV systems to 50 years. Critical interfaces and conductors must be capable of maintaining low-resistance electrical pathways despite thermal cycling, moisture ingress, mechanical loading, and other environmental challenges. At the utility scale, PV system designs that increase the mechanical robustness of cabling interfaces, such as the attachment point to a tracker or designs that increase the installation speed of a PV plant, may result in lower levelized cost of electricity through lower operation, management, and capital expenditure costs.

2.1.4.2 Geothermal Energy
For electricity-producing geothermal power plants, materials and technologies must be designed for use in harsh downhole environments with elevated temperatures of greater than 225°C. For direct use applications, temperatures are typically lower than for electricity-producing power plants, but many similar technical challenges exist. Key applications include,

- Improved wellbore materials such as high-conductivity cement or grout.
- Working fluids that optimize the net energy capture.
- Improving the thermal conductivity within the geothermal reservoir.

There is a need for innovative research and development projects using enhanced conductivity materials or technologies in subsurface reservoir/wellbore environments for geothermal direct use applications and/or at electricity-producing geothermal power plants to reduce the levelized cost of heat or electricity. For both direct use and power plants, the mechanisms for how enhanced conductivity materials improve the thermal conductivity and heat transferred from the subsurface environment to the surface need to be explored.

1. U.S. Department of Energy. "GeoVision: Harnessing the Heat Beneath our Feet." Geothermal Technologies Office, U.S. Department of Energy, 2020. *https://www.energy.gov/eere/geothermal/geovision*

2.1.4.3 Wind and Water Energy

Wind energy offers many advantages and is one of the fastest growing energy sources in the world. It is cost-effective, creates jobs, enables U.S. industry growth and competitiveness, and it's a clean, sustainable, domestic energy source.

Despite its advantages, wind power faces several challenges to broader implementation. Wind power is often not the most profitable use of land. The spinning turbines may cause noise, aesthetic pollution, and impact local wildlife. One challenge of wind power that the CABLE workshop will focus on is the difficulty of transmitting large amounts remote wind power from where the resource is greatest to cities, where the power demand is greatest. Another is the challenge of improving the efficiency of the generator component of the wind turbine.

Generators that transform mechanical to electrical energy are the backbone of the electric grid and are used in fossil energy as well as all types of renewable energy. In 2019, the U.S. used 37.1 quadrillion Btu (quads) of primary energy to generate electricity for the grid and consumed approximately 13.8 quads of site electricity in 2018 [1,2]. Of this, nearly 98% of the electricity came from mechanical generators [3].

Mechanical generators are also the oldest type of power generation as they have been used in dams for more centuries applications. Recent growth in the renewable energy sector has highlighted the need for more flexible, efficient, and reliable generator technologies—particularly in distributed applications where innovation is needed to lower costs. Conventional grid connected generators are heavy and have a large form factor, while distributed renewable systems must survive in harsh or extreme conditions, and often in remote and difficult to access locations (e.g. geothermal and offshore wind and marine energy). This results in higher transportation and installation, operations, and maintenance costs and in some cases, the need for complex thermal management systems. (e.g. operations and maintenance costs of $46/kW for for offshore wind compared with $20/kW for onshore centralized fossil generation [3]).

1. "U.S. Energy Consumption by Source and Section, 2019." EIA, 2019, *https://www.eia.gov/totalenergy/data/monthly/pdf/flow/css_2019_energy.pdf*
2. "U.S. Electricity Flow, 2018." EIA, 2018, *https://www.eia.gov/totalenergy/data/monthly/pdf/flow/electricity.pdf*
3. U.S. Energy Information Administration. "Electricity Data Browser." EIA, 2020, https://www.eia.gov/electricity/data/browser/

2.2 Materials

Most electrical conductors are composed of a pure or alloy of metallic elements, typically aluminum, copper, silver, and gold (see Table 1). Recently, composite and non-metallic conductors have been of interest due to the theoretical and experimentally determined possibility of increasing the electrical conductivity and other properties of the conductor beyond historical maximum values.

2.2.1 Metals

Metals and metal alloys, such as listed in Table 1, are currently used for nearly all electrical conductors. There are two metals that dominate most applications.

1. **Aluminum**: Aluminum is primarily used for overhead transmission lines, as it provides the benefits of high-conductivity and light-weight for low cost. The most common aluminum-based conductors are aluminum conductor steel reinforced, but other on-the-market options include aluminum conductor composite core, aluminum conductor composite reinforced, and aluminum conductors steel supported. Advanced manufacturing methods may yield unique advancements for aluminum-based conductors.
2. **Copper**: Copper offers the benefit of high electrical and thermal conductivity along with high strength. Copper-based conductor cables are typically used in medium to low voltage line applications and are used in underground applications and applications with extra-high voltages up to 400 kV because of their higher conductivity and lower corrosivity compared to Aluminum. Copper composites are also well suited for underground and underwater transmission lines. Because of their much higher conductivity, in applications where weight is not a critical factor, copper is the conductor of choice for electrical applications in most motors and generators and electrical appliances.

Table 1. Listing the most commonly used metallic conductors and their properties.

Element	%IACS	Notes
Silver (Ag)	105	Used for premium applications
Copper (Cu), pure	103	• Less expensive than silver. • Pure Cu has poor mechanical properties.
Copper (Cu)*, annealed	100	
Gold (Au)	71	• High cost • Corrosion resistant
Aluminum (Al) alloy for electric applications	~62	• Low cost • Lightweight and flexible.

2.2.2 Metal/Nanocarbon

Metal-carbon conductors are metals that contain carbon nanotubes, single or few-layer graphene, doped or undoped, or other carbon allotropes [1]. While conductivities of > 20% IACS have been observed by several groups, none of these values are for microscale and larger samples.

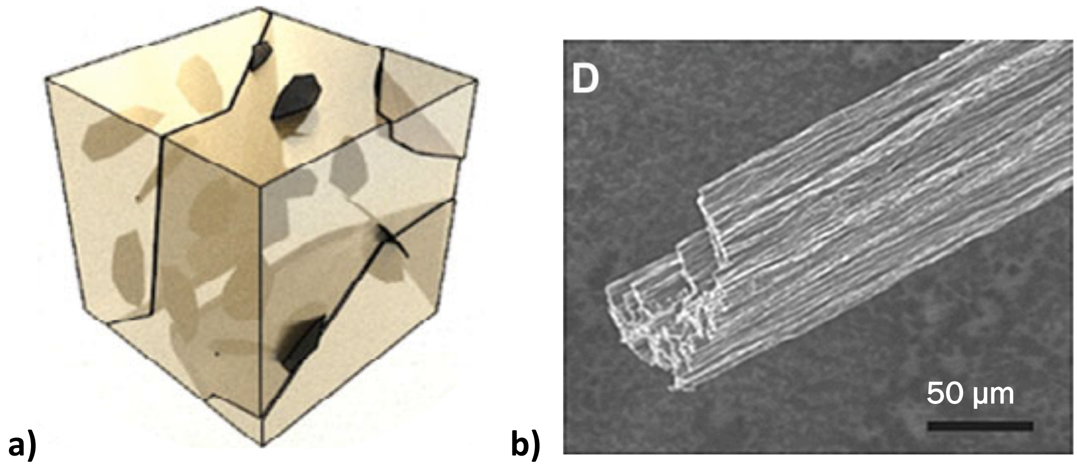

Figure 1 a) Schematic of a metal enhanced with nanocarbon [1], b) SEM image of doped graphene for application in electrical conductors [2].

There have been some measurements of graphene and the single walled carbon nanotubes (SWCNTs) electric and thermal conductivities as a function of the unintentional impurities present and their crystalline structures. These conductive properties depend, in ways still being discovered, on their processing approach. In addition, because there is no standard (e.g., grading) of the widely varying qualities of graphene, property comparison is very challenging, confusing, and tedious. In a pure physics sense, graphene is a monolayer of sp2 carbon rings. However, materials comprising as many as 10 such sp2 carbon monolayers are also referred to as graphene. But even a couple additional monolayers of graphene disrupt the graphene pi-cloud structure and lower the conductivity and other performance metrics compared to monolayer graphene. For conductivity in particular, the presence of defects in graphene structure, such as hepta-rings, penta-rings or grain boundaries, can lead to lowered electron velocities. The defect density of monolayer graphene can be measured using Raman spectroscopy and can become a tangible method for defining graphene quality. The arrangement of the carbon atoms at the edges of graphene monolayers is also a major contributor to the electronic properties of graphene. Armchair arrangement vs. zigzag arrangements influence the conductive behavior of the monolayers, especially at heterogeneous interfaces.

1. Tehrani, M., "Advanced Electrical Conductors: An Overview and Prospects of Metal Nanocomposite and Nanocarbon Based Conductors" Physica Status Solidi (a), 2000704 (2021). https://doi.org/10.1002/pssa.202000704
2. Liu, Y., Xu, Z., Zhan, J., Li, P., and Gao, C. (2016). Superb electrically conductive graphene fibers via doping strategy. Adv. Mater. 28, 7941–7947. doi: 10.1002/adma.201602444

2.2.3 Metal without Nanocarbon

These conductors are primarily the "parent" conductor metal, with small amounts of other metal or non-nanocarbon compounds. Additives explored for conductors include rare earth and transition metals. Most enhanced conductivity approaches for metal without nano-carbon have a strong focus on processing especially cold working.

2.2.4 Non-metallic Conductors

There is the possibility to increase the electrical, and thermal conductivity, of non-metallic materials. Non-metallic conductors with high electrical conductivity may have application as high thermally conductive materials. Potential advantages of non-metallic enhanced conductivity materials are the application to heat exchangers suitable for condensers or evaporators in air conditioners, heating-only heat pumps, and heat exchangers suitable for both condensing and evaporating for reversible heat pumps [1]. Non-metallic materials may also be lighter-weight, offering benefits to land vehicles, power stations, and aerospace applications.

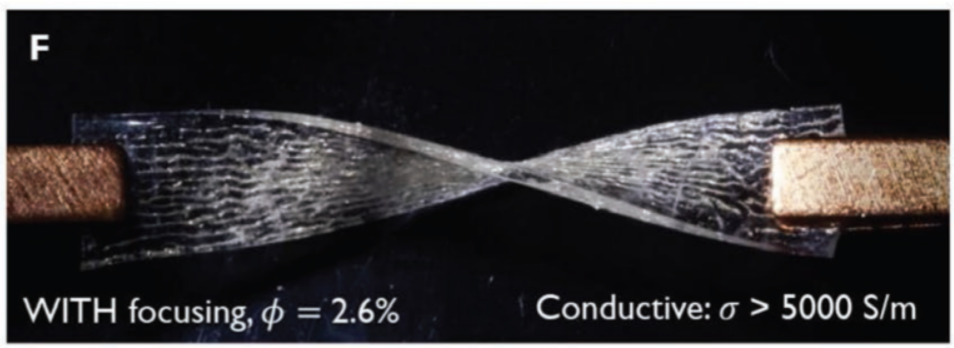

Figure 2 Example of an electrically conductive elastomeric composite material [2].

Prior R&D investments by DOE have funded explorations of high-performance compact heat exchangers, low charge heat exchanger designs, and rotating designs. The development of polymer or non-metal heat exchange designs are ideal due to their light weight, manufacturing potential, wide range of geometric design possibilities, corrosion resistance, and potential to be low cost. Despite their advantages, polymer heat exchangers have not proven effective as a practicable solution due to their relatively low thermal conductivity.

1. Rupprecht L. "Conductive Polymers and Plastics in Industrial Applications," Plastics Design Library, Norwich, NY, 1999. https://www.sciencedirect.com/book/9781884207778/conductive-polymersand-plastics
2. Melchert, D.S., Collino, R.R., Ray, T.R., Dolinski, N.D., Friedrich L., Begley, M.R., and Gianola, D.S., "Flexible Conductive Composites with Programmed Electrical Anisotropy Using Acoustophoresis", Adv. Mater. Technol. 2019, 4, 1900586, DOI: 10.1002/admt.201900586

2.2.5 Material Theory, Modeling, Computation

In the past, most enhanced electrically conductive materials were found through experimental trial and error. An alternative, and more likely to inspire investor confidence method for identifying ideal material combinations and nano- and micro-manufacturing methods is through theory, modeling, and computation.

In a recently published report, first-principles material modeling was determined to be critical for the advancement of understanding of electrical conductivity in hybrid, and homogenous, materials [1].

The primary challenge for the community is demonstrating scalable and validated approaches to overcome the cost of first-principles calculations. Extending the length scale to realistic regimes with grain boundaries and defects will allow the community to understand the materials processing challenges. Exploration of possible ways of maintaining the accuracy of the electronic structure and transport calculations will be required for making quantitative predictions to guide materials design decisions in this domain.

Such modeling can take into account several parameters including micro-nano structural geometries, contact morphology, temperature, strain, and electric/magnetic fields. Successful first-principles modeling gives us a complete understanding of the physics involved in the phenomenon. This complete understanding, once verified, permits us to then predict the material characteristics with a large span of parameters [2]. Theoretical models, once understood, can then be used with computation techniques to identify optimal material combination and parameters that may lead to enhanced electrically-thermally conductive materials with desired mechanical properties.

1. Lee, D. F. et al. "Priority Research Areas to Accelerate the Development of Practical Ultra-Conductive Copper Conductors," ORNL/TM-2015/403, 2015. https://info.ornl.gov/sites/publications/files/Pub58011.pdf
2. Kasap, S., Koughia, C., Ruda, H.E., "Electrical Conduction in Metals and Semiconductors," Springer Handbook of Electronic and Photonic Materials, 2017. DOI 10.1007/978-3-319-48933-9_2 https://info.ornl.gov/sites/publications/files/Pub58011.pdf

2.3 Supply and Characterization

When developing the next-generation of breakthrough electrical conductor materials, the abundance of a material is a crucial consideration to implementing large-scale manufacturing and distribution. In addition to electrical conductivity, other properties of the materials are as essential in ensuring reliable service in harsh environments for extended duration.

2.3.1 Supply Chain

Conductors rely primarily on three metals to enhance their properties: Aluminum, Copper, and Silver. An important consideration all enhanced conductors is the supply chain from production to consumption. The supply chain directly impacts the cost and availability of each metal and plays a role in the ability to rely on each metal in enhanced conductors as they are scaled-up.

Aluminum

Aluminum is the lowest-cost metal of the three and is the most available. Most new aluminum are created by processing bauxite ore. China produces about 10 times

more aluminum than any other country (about 37 million tonnes per year) and accounts for over half of all new production [1]. Despite its abundance, the extraction of aluminum from ore is an energy extensive and polluting process that makes recycling an attractive alternative. The U.S. is a net importer of aluminum, though was able to supply around 45% of its consumption needs (2.9 million tonnes total) from scrap in 2019. Canada is the biggest importer of aluminum into the United States providing roughly half of all imports [1].
Aluminum has many uses including applications in packaging, transportation, building, machinery, and electrical systems. Aluminum is available for consumption in seven different alloy series going from the 1000 series to the 7000 series. Each alloy has its own performance characteristics that may be better suited for a given application. Global aluminum supplies are expected to be sufficient for the distant future and with robust supply lines and the metals abundance, the cost of aluminum has remained low over time and currently around $1/pound [2]. Aluminum has seen a price increase over the past year since the onset of the COVID-19 pandemic.

Copper
Copper is found is two types of deposits (porphyry deposits and sediment-hosted deposits) and can be extracted from two types of ores (sulfide and oxide). Once extracted, copper must be refined in smelters before end use [4]. Therefore, there are separate but related supply lines tied to copper ores and refined copper. Chile is the largest producer of copper ore (5.7 million tonnes) with China being the biggest producer of refined copper (9.8 million tonnes) and the largest importer of both [5]. The United States is the second largest importer of refined copper. The grades of copper produced from mines has been decreased over the last few decades, and new supplies of copper may be necessary to prevent future shortages. Similar to aluminum, recycling of copper has kept much of the existing supply in circulation which alleviates some supply concerns.
The U.S. consumed around 1.6 million tonnes of Copper in 2020, relying on imports for less than 50% of its demand. These imports are supplied typically from Canada, Mexico, and Chile [3]. Copper is an attractive metal for use in a variety of applications due to its ductility, malleability, conductivity, and resistance to corrosion. It is heavily used in industrial applications, but its largest use is in building construction. Other applications include for electrical wires, transportation, machinery, and consumer products. Copper can be alloyed with a number of different metals and be included at a variety of concentrations which results in a large number of available alloys and classifications on the market. Copper prices have nearly doubled over the past year and currently sit around $4/pound [3]. There has been a steady upward trend in copper prices over the past several decades as well.

Silver
Silver is the rarest of these three metals and is the most expensive. It also relies the least on recycling for new material supply because a lot of silver is used as a store of value. Only 8% of silver supply in the U.S. is provided by recycling of new

and old scrap. Silver is mined from polymetallic ore deposits before refining into its base metal. Mexico and Peru (5,600 tonnes and 3,400 tonnes respectively) are the two largest producers of silver and account for 36% of global production [4]. The consumption of silver in the U.S. is 8,000 tonnes and therefore many orders of magnitude less than both aluminum and copper [6]. Most domestic silver is imported primarily from Mexico (50%) and the United States is one of the largest consumers of silver in the world. Due to silvers ductility, conductivity, malleability, reflectivity, and rarity it has many applications including for electronics, coins, photography, jewelry and silverware, water conversion, solar PVs, and antimicrobial bandages. Its most common uses are for electronics, jewelry and silverware, and coins (around 70% of uses combined) [6]. There are a number of silver grades and alloys which are primarily focused on their silver content due to silver's high value. Silver prices can fluctuate wildly due to its use as a value commodity and current prices have seen an increase over the past year. Silver currently costs around $25 dollars per troy ounce ($365 per pound) [5].

Nanocarbons

Nanocarbons are an emerging market with a growing supply chain which will have to deal with increased scale-up and quality control issues. In addition to structural defects and number of layers, graphene performance also depends on impurities present in its structure. Few-layer or many-layer graphene, typically manufactured from delamination of graphite using Hummers' method or super-acid synthesis, followed by pyrolization, is also referred to as reduced graphene oxide (rGO). While casually referred to as graphene, rGO occurs as a 'black' powder and is one of the more impure forms of few-layer graphene. True to its name, rGO is made from pyrolyzed graphene oxide. Graphene oxide has a physical structure similar to few-layer graphene; the key difference is that the pi-cloud electrons are used to form chemical reactions to leave functional groups along the surface of the graphene layers, which induces several physical structural defects along the layers, as well as in between the layers. Pyrolization of this graphene oxide leads to reduction of some of the functional groups; however, the process is not 100% efficient and as such there are several impurities on the few-layer rGO 'particle' surfaces and in between the layers as well. rGO is cheaper to procure and is available in large quantities commercially, but typically demonstrates very low electronic properties. On the other hand, high purity, low defect density monolayer graphene, manufactured via chemical vapor deposition, molecular beam epitaxy, physical vapor deposition, or arc deposition among other methods is >97% transparent and demonstrates ultra-high electron velocities, which are even greater than that of carbon nanotubes. The International Standards Organization (ISO) has begun to develop categories of purity for nanocarbons such as graphene but as of yet, there are no standards or regulations for nanocarbon materials in the U.S.

Other Materials

Other supporting materials for enhanced conductors such as metal nanoparticles, rare earths, and transition metals each rely on separate supply chains with their own characteristics. Some of the rare earths of interest rely heavily on single countries as a source for the material. That can present a risk in case of supply disruptions. The risks and benefits of each material's supply chain is an important consideration when scaling-up production of enhanced conductors.

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2.3.2 Non-Conductivity Properties and Characterization

In CABLE, breakthroughs in one property must be complemented by maintaining the other properties above minimum accepted values, with minimum standards to be developed for each major application described in Section 2.1.
For example, desired properties of conductors for EDS applications include:

- High ampacity
- Reduced Skin effect
- High tensile strength for maximized reliability
- Low coefficient of thermal expansion for decreased sag
- Low density for decreased weight
- High bending fatigue strength
- High thermal conductivity for heat dissipation
- High operating temperature
- High ductility for mechanical flexibility
- Earth-abundant content for minimized cost
- Recyclable and safe material for end-of-life consideration

Full and fundamental understanding of enhanced conductivity and other properties sometimes requires facilities well beyond the reach of the typical inventor. For example, the Argonne National Laboratory's Advanced Photon Source is able to produce very high energy photons that can be used with an ultra-small angle scattering measurement to determine the dynamics of CABLE materials manufacturing processes at the electron level. Other national laboratory facilities of interest to CABLE materials inventors include,

- E-Beam and Laser Powder Bed Fusion Additive Manufacturing facilities at the Oak Ridge National Laboratory's Manufacturing Demonstration Facility
- ShAPE™ (Shear Assisted Processing and Extrusion) machines at the Pacific Northwest National Laboratory
- Covetics Furnace at the National Energy Technology Laboratory.

2.3.3 Conductivity Measurement

Electrical conductivity of materials is generally measured in the units of Siemens (S), where one Siemen is equivalent to one Amp per Volt and is the reciprocal of the electrical resistance. Though the units of Siemens are common in scientific literature, a more common standard used in industry for the measurement of electrical conductivity is called the International Annealed Copper Standard (IACS). The IACS is a comparative value of the percent difference of the electrical conductivity of pure copper at 20°C.

Thermal conductivity is often measured indirectly by measuring thermal diffusivity. Thermal diffusivity is the speed with which heat propagates through a material. It has a multitude of direct applications, such as determining heat transfer through brake pads at the moment of contact, etc., but more often it is used to derive thermal conductivity from the fundamental relationship tying it with specific heat capacity and density which also have their own measurement challenges. The best option is often to measure specific heat capacity can be obtained parallel with thermal diffusivity. Thus, a single test yields thermal diffusivity and thermal conductivity with prior knowledge of density. The method is fast and produces results with high accuracy and very good repeatability.

Conclusion

It seems clear that it is possible to manufacture high electrical conductivity materials, as demonstrated by recent research results. It is the goal of the DOE, EERE, AMO, and the CABLE Initiative that the barriers and gaps of fundamental knowledge of electrical conductivity are overcome and that these materials are easily manufactured at competitive cost. Achieving these goals will lead the U.S. to greater energy independence, reduce GHG emissions, and result in a more robust and efficient energy grid.